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14. ABSTRACT In this project, we developed high-level, human-like specification languages for robotic motion tasks and computational frameworks for automatic synthesis of robot control and communication strategies from such specifications. Central to our approach are finite abstractions, which allow for the use of (adapted) temporal logics as specification languages, tools from formal verification resembling model checking for analysis and control, and techniques inspired from synchronization in concurrency theory for synthesis of communication strategies. In short,					
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Report Title

Specification languages and distributed control schemes for teams of unmanned vehicles

ABSTRACT

In this project, we developed high-level, human-like specification languages for robotic motion tasks and computational frameworks for automatic synthesis of robot control and communication strategies from such specifications. Central to our approach are finite abstractions, which allow for the use of (adapted) temporal logics as specification languages, tools from formal verification resembling model checking for analysis and control, and techniques inspired from synchronization in concurrency theory for synthesis of communication strategies. In short, the results of this project can be grouped into: (1) computational tools for abstraction and temporal logic analysis and control of one dynamical system and (2) computational frameworks for automatic synthesis of control and communication strategies for a robotic team from global specifications given as temporal logic statements over a set of environmental service requests.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
2011/09/04 0: 6	X. C. Ding, A. Stefanescu, C. Belta, Y. S. Chen. Temporal Logic Motion Planning and Control with Probabilistic Satisfaction Guarantees, IEEE Transactions on Robotics, (12 2011): 0. doi:

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
2011/08/28 2: 9	Boyan Yordanov, Jana Tumova, Calin Belta, Ivana Cerna, Jiri Barnat. Temporal Logic Control of Discrete-Time Piecewise Affine Systems, IEEE Transactions on Automatic Control, (12 2011): 0. doi:
2011/08/28 2: 8	Xu Chu Ding, Marius Kloetzer, Yushan Chen, Calin Belta. Formal Methods for Automatic Deployment of Robotic Teams, IEEE Robotics and Automation Magazine, (12 2011): 0. doi:

TOTAL: 2

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(c) Presentations

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
2011/08/25 2: 1	Xu Chu Ding, Stephen L. Smith, Calin Belta, Daniela Rus. LTL Control in Uncertain Environments with Probabilistic Satisfaction Guarantees, IFAC 2011. 2011/08/29 00:00:00, . : ,

TOTAL: 1

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
2011/08/28 2: 11	A. I. Medina Ayala, S. B. Andersson, C. Belta. probabilistic forma synthesis, robot motion planning and control, IEEE IROS. 2011/09/20 00:00:00, . : ,
2011/08/28 2: 10	Alphan Ulusoy, Stephen L. Smith, Xu Chu Ding, Calin Belta, Daniela Rus. Optimal Multi-Robot Path Planning with Temporal Logic Constraints, IEEE IROS. 2011/09/27 00:00:00, . : ,
2011/08/25 2: 5	M. Lahijanian, S. B. Andersson, C. Belta. Temporal Logic Control for Markov Decision Processes, ACC 2011. 2011/06/29 00:00:00, . : ,
2011/08/25 2: 4	Yushan Chen, Xu Chu Ding, Calin Belta. Synthesis of Distributed Control and Communication Schemes from Global LTL Specifications, CDC 2011. 2011/12/09 00:00:00, . : ,
2011/08/25 2: 3	Xu Chu Ding, Stephen L. Smith, Calin Belta, Daniela Rus. MDP Optimal Control under Temporal Logic Constraints, CDC 2011. 2011/12/09 00:00:00, . : ,
2011/08/25 2: 2	Igor Cizelj, Xu Chu Ding, Morteza Lahijanian, Alessandro Pinto, Calin Belta. Probabilistically Safe Vehicle Control in a Hostile Environment, IFAC 2011. 2011/08/29 00:00:00, . : ,

TOTAL: 6**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
2011/10/24 1: 12	Y. S. Chen, X. C. Ding, A. Stefanescu, C. Belta. A Formal Approach to the Deployment of Distributed Robotic Teams, (10 2011)

TOTAL: 1**Number of Manuscripts:**

Books

<u>Received</u>	<u>Paper</u>
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TOTAL:**Patents Submitted**

Patents Awarded

Awards

Plenary Invited Speaker, 15th International Conference on Hybrid Systems: Computation and Control (HSCC) Beijing, April 17, 2012.

Best Student Paper Award, (student: Yushan Chen), 10th Int. Symp. on Distributed Autonomous Robotic Sys, Lausanne, Switzerland, 2010

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Jana Tumova	0.20
Maria Svorenova	0.20
FTE Equivalent:	0.40
Total Number:	2

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Calin Belta	0.10	
FTE Equivalent:	0.10	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Total Number:

Names of personnel receiving PHDs

<u>NAME</u>
Boyan Yordanov
Morteza Lahijanlian
Total Number:
2

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attachment

Technology Transfer

ABSTRACT

In this project, we developed high-level, human-like specification languages for robotic motion tasks and computational frameworks for automatic synthesis of robot control and communication strategies from such specifications. Central to our approach are finite abstractions, which allow for the use of (adapted) temporal logics as specification languages, tools from formal verification resembling model checking for analysis and control, and techniques inspired from synchronization in concurrency theory for synthesis of communication strategies. In short, the results of this project can be grouped into: (1) computational tools for abstraction and temporal logic analysis and control of one dynamical system and (2) computational frameworks for automatic synthesis of control and communication strategies for a robotic team from global specifications given as temporal logic statements over a set of environmental service requests.

REPORT

The results of this 3-year project include: (1) Computational frameworks for abstraction and Linear Temporal Logic (LTL) verification and control of discrete-time linear systems; (2) A computational framework for LTL control of continuous-time multi-affine dynamics with time constraints; (3) Tools for Markov Decision Process (MDP) control from specifications given as Probabilistic Computation Tree Logic (PCTL) formulas; (4) Tools for Markov Decision Process (MDP) control from specifications given as Probabilistic LTL (PLTL) formulas; (5) Tools for continuous-time Markov Decision Process (CTMDP) control from specifications given as Continuous Stochastic Logic (CSL) formulas; (6) Computational frameworks for automatic synthesis of (optimal) control and communication strategies for robotic teams from global specifications given as Regular Expressions (RE) and LTL formulas over sets of environmental service requests; (7) Computational tool for LTL robot control based on automata learning of environmental dynamics. For all of the above, we performed experimental validations.

In the following, we provide more details on these results. The corresponding papers are cited by first author, conference or journal abbreviation, and year of publication.

(1) Abstraction and LTL verification and control of discrete-time linear systems

As part of the first objective of the initial proposal, in [Yordanov IEEE TAC 2012, Tumova CDC 2010] we developed a computational framework for automatic synthesis of a feedback control strategy for a piecewise affine (PWA) system from a specification given as a Linear Temporal Logic (LTL) formula over an arbitrary set of linear predicates in its state variables. Our approach consists of two main steps. First, by defining appropriate partitions for its state and input spaces, we construct a finite abstraction of the PWA system in the form of a control transition system. Second, by leveraging ideas and techniques from Rabin games and LTL model checking, we develop an algorithm to generate a control strategy for the finite abstraction. While provably correct and robust to

small perturbations in both state measurements and applied inputs, the overall procedure is conservative and expensive.

In [Yordanov IEEE TAC 2010, Yordanov CDC 2010], we developed a computational framework for identifying a set of initial states from which all trajectories of a piecewise affine (PWA) system satisfy a Linear Temporal Logic (LTL) formula over a set of linear predicates in its state variables. Our approach is based on the construction and refinement of finite abstractions of infinite systems (i.e. systems where states can take infinitely many values). We derive conditions guaranteeing the equivalence of an infinite system and its finite abstraction with respect to a specific temporal logic formula and propose methods aimed at the construction of such formula-equivalent abstractions. We show that the proposed procedure can be implemented using polyhedral operations and analysis of finite graphs.

Both tools described above were implemented as user-friendly packages available for download at our website hyness.bu.edu/software. It is important to note that PWA systems are quite general, since they can approximate nonlinear dynamics (such as aircraft dynamics) with arbitrary accuracy. In addition, there exist several computation tools for the identification of such models from input-output experimental data.

(2) A computational framework for LTL control of continuous-time multi-affine dynamics with time constraints

In [Aydin-Gol ADHS 2012], we considered the problem of controlling a dynamical system such that its trajectories satisfy a temporal logic property in a given amount of time. We focused on multi-affine systems and specifications given as syntactically co-safe linear temporal logic formulas over rectangular regions in the state space. The proposed algorithm is based on the estimation of time bounds for facet reachability problems and solving a time optimal reachability problem on the product between a weighted transition system and an automaton that enforces the satisfaction of the specification. A random optimization algorithm was used to iteratively improve the solution.

(3) MDP Control from PCTL Specifications with Applications to Robot Motion Planning and Control

In [Lahijanian ICRA 2010, Lahijanian ACC 2011, Lahijanian TRO 2011], we considered a robot that moves in a partitioned environment by applying a given set of motion primitives allowing it to steer between adjacent regions. Due to sensor and actuation noise, while applying an available motion primitive at a region, the robot can transit to more than one adjacent regions. We assume that the probabilities of these transitions are known. We also assumed that the robot could determine its current region precisely. In indoor environments, such an assumption is not overly restrictive since simple environment modifications can be made to enforce it, such as placing a large number of radio frequency identity (RFID) tags. We solved this problem by abstracting the robot motion to an MDP and deriving an algorithm to synthesize control strategies from specifications given as PCTL formulas. Examples of such specifications include

“Eventually reach A and then B with probability greater than 0.9 while always avoiding the regions from which the probabilities of converging to C is greater than 0.2” and “Eventually reach a region from which the probability of converging to A is 0.8 while minimizing the total amount of travel time”.

In short, given a specification as a PCTL formula, the algorithm returns the maximum probability or the minimum cost of satisfaction and a control strategy that achieves this probability or cost. Our algorithm uses sub-algorithms corresponding to each temporal operator as building blocks for the construction of a control strategy from a formula with multiple temporal operators. The most computationally expensive sub-algorithm requires solving a linear programming problem.

We illustrated the method in our Robotic InDoor Environment, in which an iRobot iCreate platform equipped with RFID readers and a laser range finder moves autonomously through the corridors and intersections of an easily reconfigurable environment.

In [Cizelj IFAC 2011], we developed an approach to design a reactive control strategy that provides probabilistic guarantees of accomplishing the mission in a threat-rich environment. This control strategy is reactive in the sense that the control of the vehicle is updated whenever the vehicle reaches a new region in the environment, or an adversary moves in between the current region and its adjacent region (i.e. if the vehicle observes movements of adversaries, it updates the adversary distributions for adjacent regions and chooses a different control action as needed). In order to solve this problem, we capture the motion of the vehicle, as well as vehicle estimates of the adversary distributions in a MDP. This way, we map the vehicle control problem to the problem of finding a control policy for an MDP such that the probability of satisfying a PCTL formula is maximized. For the latter, we used the MDP control approach described above.

In [Medina IROS 2011], we consider an extension of the PCTL control problem described above by allowing for a dynamic (changing) environment. Specifically, the environment includes doors that open and close during the robot's mission. We solve this problem under three settings that assume different levels of knowledge and sensing capabilities of the robot. In the first setting the robot is given *a priori* information about the states of the doors, but it can only learn their true states in a region adjacent to them. The second setting excludes the prior information about the states of the doors but retains the assumption that the exact state of any door is known when the robot is in a region adjacent to it. In the last setting, this assumption is also relaxed and we allow for possibly erroneous measurements as to the state of the doors observed by the robot. A Markov decision process (MDP) is used to model the system under the first setting. The second and third settings are cast as mixed observable Markov decision processes (MOMDPs). We consider specifications given as PCTL formulas and develop a framework for the synthesis of control strategies from such specifications. While this paper focuses for clarity on an indoor environment with doors, the problem and methods developed can easily be generalized to arbitrary environments with regions in which the transitions can be open or blocked. To illustrate these methods, we used the Robotic InDoor

Environment (RIDE) Simulator to generate the MDP and MOMDP models for a robot moving in a dynamic environment and to show the planning of the robot.

(4) MDP Control from Specifications given as PLTL Formulas with Applications to Robot Motion Planning and Control

In [Ding IFAC 2011], we presented a method to generate a robot control strategy that maximizes the probability to accomplish a task. The task is given as a Linear Temporal Logic (LTL) formula over a set of properties that can be satisfied at the regions of a partitioned environment. We assume that the probabilities with which the properties are satisfied at the regions are known, and the robot can determine the truth value of a proposition only at the current region. Motivated by several results on partitioned-based abstractions, we assume that the motion is performed on a graph. To account for noisy sensors and actuators, we assume that a control action enables several transitions with known probabilities. We show that this problem can be reduced to the problem of generating a control policy for a Markov Decision Process (MDP) such that the probability of satisfying an LTL formula over its states is maximized. We provide a complete solution for the latter problem that builds on existing results from probabilistic model checking.

In [Ding CDC 2011], we developed a method to automatically generate an optimal control policy for a dynamical system modeled as a Markov Decision Process (MDP). The control specification is given as a Linear Temporal Logic (LTL) formula over a set of propositions defined on the states of the MDP. We used the method described above to synthesize a control policy such that the MDP satisfies the given specification almost surely, if such a policy exists. In addition, we designate an "optimizing proposition" to be repeatedly satisfied, and we formulate a novel optimization criterion in terms of minimizing the expected cost in between satisfactions of this proposition. We propose a sufficient condition for a policy to be optimal, and develop a dynamic programming algorithm that synthesizes a policy that is optimal under some conditions, and sub-optimal otherwise.

(5) Continuous-Time MDP Control from Specifications given as CSL formulas

In [Medina, ICRA 2012], we considered a mobile robot whose performance is measured by the completion of temporal logic tasks within a certain period of time. In addition to such time constraints, the planning algorithm must also deal with changes in the robot's workspace during task execution. In our case, the robot was deployed in a partitioned environment subjected to structural changes in which doors shift from open to closed and vice-versa. The motion of the robot was modeled as a Continuous Time Markov Decision Process and the robot's mission was expressed as a Continuous Stochastic Logic (CSL) temporal logic specification. An approximate solution to find a control strategy that satisfies such specifications was derived for a subset of probabilistic CSL formulae. Simulation and experimental results were provided to illustrate the method.

(6) Automatic synthesis of (optimal) control and communication strategies for robotic teams from global specifications given as Regular Expressions (RE) and LTL formulas over sets of environmental service requests

In [Chen TRO 2012, Chen DARS 2010, Chen IROS 2010], we presented a computational framework for automatic synthesis of control and communication strategies for a robotic team from task specifications given as regular expressions about servicing requests in an environment. We assumed that the location of the requests in the environment and the robot capacities and cooperation requirements to service the requests were known. Our approach was based on two main ideas. First, we extended recent results from formal synthesis of distributed systems to check for the distributability of the task specification and to generate local specifications, while accounting for the service and communication capabilities of the robots. Second, by using a technique inspired from LTL model checking, we generated individual control and communication strategies. We illustrated the method with experimental results in our Robotic Urban-Like Environment (RULE). In [Chen CDC 2011], we extended this technique to specifications given in full LTL. Experimental validations were included as well.

In [Ulusoy IROS 2011], we presented a method for automatically planning optimal paths for a group of robots that satisfy a common high level mission specification. Each robot's motion in the environment is modeled as a weighted transition system. The mission for the robots is given as a general Linear Temporal Logic formula. In addition, an optimizing proposition must repeatedly be satisfied by the group of robots. The goal for the group is to minimize the maximum time between satisfying instances of the optimizing proposition. Our method is guaranteed to compute an optimal set of robot paths. We utilized a timed automaton representation in order to capture the relative position of the robots in the environment. We then obtained a bisimulation of this timed automaton as a relatively compact finite transition system that captured the joint behavior of the robots. We then applied our earlier algorithm for the single robot case to optimize the group motion. We presented a simulation of robots performing a persistent monitoring task in a road network environment, and characterized the complexity of our method.

(7) LTL Robot Control based on Automata Learning of Environmental Dynamics

In [Chen ICRA 2012], we developed a technique to automatically generate a control policy for a robot moving in an environment that includes elements with partially unknown, changing behavior. The robot was required to achieve an optimal surveillance mission, in which a certain request needed to be serviced repeatedly, while the expected time in between consecutive services was minimized. We defined a fragment of LTL to describe such a mission and formulated the problem as a temporal logic game. Our approach was based on two main ideas. First, we extended results in automata learning to detect patterns of the partially unknown behavior of the elements in the environment. Second, we employed an automata-theoretic method to generate the control policy. We showed that the obtained control policy converges to an optimal one when the unknown behavior patterns are fully learned. We also implemented the proposed framework in

MATLAB and used in conjunction with a simulator to demonstrate the behavior of a robot performing missions in the environment.

Personnel Supported During Duration of Grant

Yushan Chen	Graduate Student, Boston University
Ana Medina Ayala	Graduate Student, Boston University
Morteza Lahijanian	Graduate Student, Boston University
Alphan Ulusoy	Graduate Student, Boston University
Maria Svorenova	Research Scientist, Boston University
Jana Tumova	Research Scientist, Boston University
Calin Belta	Assoc Prof., Boston University

Publications

Journal publications

Morteza Lahijanian, Sean B. Andersson, and Calin Belta, Temporal Logic Motion Planning and Control with Probabilistic Satisfaction Guarantees, IEEE Transaction on Robotics, vol. 28, no. 2, pp. 396-409, 2012

Xu Chu Ding, Marius Kloetzer, Yushan Chen, Calin Belta, Automatic Deployment of Robotic Teams: An Automata Theoretic Approach, IEEE Robotics and Automation Magazine, vol. 18, no. 3, pp. 75-86, 2011

Stephen Smith, Jana Tumova, Calin Belta, Daniela Rus, Optimal Path Planning for Surveillance with Temporal Logic Constraints, International Journal of Robotics Research, vol. 30, no. 14, pp. 1695-1708, 2011

Y. Chen, D. Ding, A. Stefanescu, and C. Belta, A Formal Approach to the Deployment of Distributed Robotic Teams, IEEE Transaction on Robotics, vol. 28, issue 1, pp.158 – 171, 2012

B. Yordanov, J. Tumova, I. Cerna, J. Barnat, C. Belta, Temporal Logic Control of Discrete-Time Piecewise Affine Systems, IEEE Transactions on Automatic Control, vol. 57, no. 6, pp. 1491-1504, 2012

B. Yordanov and C. Belta, Formal analysis of discrete-time piecewise affine systems, IEEE Transactions on Automatic Control, vol. 55, no. 2, pp. 2834-2840, 2010

Pier-reviewed conference publications

Ebru Aydin Gol and Calin Belta, Time-Constrained Temporal Logic Control of Multi-Affine Systems, 4th IFAC Conference on Analysis and Design of Hybrid Systems (ADHS), Eindhoven, Netherlands, 2012

Xu Chu Ding, Mircea Lazar, and Calin Belta, Receding Horizon Temporal Logic Control

for Finite Deterministic Systems, American Control Conference, Montréal, Canada, 2012

Alphan Ulusoy, Stephen L. Smith, Xu Chu Ding, Calin Belta, Robust Multi-Robot Optimal Path Planning with Temporal Logic Constraints, 2012 IEEE International Conference on Robotics and Automation (ICRA), 2012, Saint Paul, MN, USA

Xu Chu Ding, Jing Wang, Morteza Lahijanian, Yannis Paschalidis, Calin Belta, Temporal Logic Motion Control using Actor-Critic Methods, 2012 IEEE International Conference on Robotics and Automation (ICRA), 2012, Saint Paul, MN, USA

Ana Ivonne Medina Ayala, Sean Andersson, Calin Belta, Probabilistic Control from Time-Bounded Temporal Logic Specifications in Dynamic Environments, 2012 IEEE International Conference on Robotics and Automation (ICRA), 2012, Saint Paul, MN, USA

Yushan Chen, Jana Tumova, Calin Belta, LTL Robot Motion Control based on Automata Learning of Environmental Dynamics 2012 IEEE International Conference on Robotics and Automation (ICRA), 2012, Saint Paul, MN, USA

Ebru Aydin Gol, Mircea Lazar, and Calin Belta, Language-Guided Controller Synthesis for Discrete-Time Linear Systems, Hybrid Systems Computation and Control (HSCC) 2012, Beijing, China

Marius Kloetzer, Xu Chu Ding, Calin Belta, Multi-robot deployment from LTL specifications with reduced communication, CDC 2011, Orlando, FL, 2011

Reza Moazzez Estanjini, Xu Chu Ding, Morteza Lahijanian, Calin Belta, Ioannis Paschalidis, Least Squares Temporal Difference Actor-Critic Methods with Applications to Robot Motion Control, CDC 2011, Orlando, FL, 2011

Xu Chu Ding, Stephen L. Smith, Calin Belta, Daniela Rus, MDP Optimal Control under Temporal Logic Constraints, CDC 2011, Orlando, FL, 2011

Yushan Chen, Xu Chu Ding, Calin Belta, Synthesis of Distributed Control and Communication Schemes from Global LTL Specifications, CDC 2011, Orlando, FL, 2011

Alphan Ulusoy, Stephen L. Smith, Xu Chu Ding, Calin Belta, Daniela Rus, Optimal Multi-Robot Path Planning with Temporal Logic Constraints, IROS, San Francisco, 2011

Ana Ivonne Medina Ayala, Sean Andersson, and Calin Belta, Temporal Logic Control in Dynamic Environments with Probabilistic Satisfaction Guarantees, IROS, San Francisco, 2011

M. Lahijanian, S. B. Andersson, and C. Belta, Control of Markov Decision Processes from PCTL specifications, American Control Conference (ACC), San Francisco, CA, 2011

Igor Cizelj, Xu Chu Ding, Morteza Lahijanian, Alessandro Pinto, Calin Belta, Probabilistically Safe Vehicle Control in a Hostile Environment, 18th IFAC World Congress. Milan, Italy, 2011

Xu Chu Ding, Stephen L. Smith, Calin Belta, Daniela Rus, LTL Control in Uncertain Environments with Probabilistic Satisfaction Guarantees, 18th IFAC World Congress. Milan, Italy, 2011

Y. Chen, X. C. Ding, A. Stefanescu, and C. Belta, A Formal Approach to Deployment of Robotic Teams in an Urban-Like Environment, 10th International Symposium on Distributed Autonomous Robotics Systems (DARS), Lausanne, Switzerland, 2010 (Best student paper award)

Jana Tumova, Boyan Yordanov, Calin Belta, Ivana Cerna, Jiri Barnat, A Symbolic Approach to Controlling Piecewise Affine Systems, IEEE Conference on Decision and Control (CDC), Atlanta, GA, 2010

Boyan Yordanov, Jana Tumova, Calin Belta, Ivana Cerna, Jiri Barnat, Formal Analysis of Piecewise Affine Systems through Formula-Guided Refinement, IEEE Conference on Decision and Control (CDC), Atlanta, GA, 2010

Xu Chu Ding, Calin Belta, Christos G. Cassandras, Receding Horizon Surveillance with Temporal Logic Specifications, IEEE Conference on Decision and Control (CDC), Atlanta, GA, 2010

Y. Chen, A. Stefanescu, and C. Belta, A Hierarchical Approach to Automatic Deployment of Robotic Teams with Communication Constraints, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Taipei, Taiwan, 2010

S. L. Smith, J. Tumova, C. Belta, and D. Rus, Optimal path planning under Temporal Logic Constraints

M. Lahijanian, J. Wasniewski, S. B. Andersson, and C. Belta, Motion Planning and Control from Temporal Logic Specifications with Probabilistic Satisfaction Guarantees, IEEE International Conference on Robotics and Automation (ICRA 2010), May 3-8, 2010, Anchorage, Alaska, USA

M. Kloetzer, S. Itani, S. Birch, and C. Belta, On the Need for Communication in Distributed Implementations of LTL Motion Specifications, IEEE International Conference on Robotics and Automation (ICRA 2010), May 3-8, 2010, Anchorage, Alaska, USA

B. Yordanov and C. Belta, Temporal Logic Control of Discrete-Time Piecewise Affine Systems, IEEE Conference on Decision and Control (CDC), Shanghai, China, pp. 3182-3187, 2009

M. Lahijanian, C. Belta, and S. Andersson, A Probabilistic Approach for Control of a Stochastic System from LTL Specifications, IEEE Conference on Decision and Control

(CDC), Shanghai, China, pp. 2236 – 2241, 2009